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14. ABSTRACT
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This paper describes graceful degradation and its accompanying concepts, and applies them to Command and Control theory. It argues that graceful degradation needs to be designed into our organizational as well as our technological C2 systems. It points out that the new emphasis on mission command is one necessary and desirable approach to incorporating graceful degradation in Command and Control, but it is insufficient. The paper concludes that graceful degradation needs to be inculcated in the minds of leaders such that they apply the concept as a matter of course, rather than conscious application. The paper includes cases illustrating the points of argument.

Setting – A Historical Example

About 0125 hours, Friday, 13 November 1942, an American naval task force intercepted a powerful Japanese naval force en route to a bombardment mission off Guadalcanal. The USS SAN FRANCISCO, a heavy cruiser, was the flagship of the Americans. At pointblank range for naval engagements, less than 3,000 meters, the Americans opened fire. After forty-five minutes of brutal exchanges of naval gunfire, both sides withdrew, the Americans claiming a victory of sorts because the Japanese did not complete the bombardment of American positions on Guadalcanal. Eight of the thirteen American ships were sunk by the Japanese and all but one of the survivors suffered moderate to heavy damage. One of the survivors was the SAN FRANCISCO; the ship received forty-five hits from guns ranging in size from five inch to fourteen inch. During the battle, the SAN FRANCISCO received a direct hit to the command and control center of the ship, the navigation bridge. The senior surviving officer transferred command to the alternate command post known as Battle Two. Then, a Japanese shell disabled Battle Two. The ship's acting commander transferred command back to the bridge. Finally, another enemy round again hit the bridge, disabling command and control. Remarkably, even without electronic communications, the commander was able to reestablish engine control and

steering with fire control under local command. The SAN FRANCISCO continued to fire into the enemy throughout the several instances of loss of command and control and finished the battle. Eventually, the ship returned to Mare Island Naval Base for repairs and served in several subsequent naval campaigns, ending naval service in 1946.[1]

Introduction

This paper introduces the systems concept of graceful degradation to the discussion of military command and control. Graceful degradation is a desirable characteristic – a virtue as described herein - of systems that allows them to continue functioning with some capacity even with the failure of some critical components and processes, with the functionality proportionate to the failure(s). The above vignette concerning the USS SAN FRANCISCO during the First Naval Battle of Guadalcanal serves as an excellent illustration of what command and control graceful degradation looks like in real operations. This characteristic has three related facets, in the context of living, specifically human-in-the-loop systems: (1) hardware or equipment; (2) software, doctrine, or procedures that prescribe how to use the hardware; and (3) the human(s) who operate the hardware using the software associated with the equipment. To illustrate these relationships, consider in the preceding vignette that the ship and its various subsystems to be the hardware, the software or standard operating procedures informed the surviving leaders how and where to locate command and control of the ship, and the humans involved were the key leaders of the crew.

To accomplish its task, the paper progresses through four sections. Following this first introductory section, it secondly provides definitions and context of the term and its close conceptual relative, resiliency. Third, the paper briefly examines six historical cases, three considering successful human, software and hardware aspects of graceful degradation, and three considering unsuccessful aspects. Fourth and finally, the paper concludes with some observations and recommendations on future research and practice incorporating the graceful degradation virtue.

Graceful Degradation in Context

Various terms have been used in the past to describe the ability of a system to continue functioning, at least for a time, after critical processes or sub-systems are compromised or destroyed. The terms fault tolerance, fault tolerance computing, and graceful degradation were all used within the systems engineering discipline to describe the property(ies) that enables a system to continue operating properly in the event of the failure (or one or more faults within) some of its components. Within the materials science field, the term resilience has been used to understand the behavior and properties of specific materials when an external force is applied to the material. More recently, the resilience concept has been applied in a number of other discrete fields such as: psychology, socio-ecological systems, disaster response, and critical

infrastructure protection. Each of these domains has viewed the graceful degradation or resilience concept from the perspective of the problems they were trying to solve, hence there is no unified theory or concept of resilience.[2] However, two related concepts – robustness and redundancy – are common throughout the discussions and each of these fields and their perspective of resilience have insights which can assist in designing future military C2 systems. This paper conceives of the relationship between resilience and graceful degradation to be similar to that of output and outcome of a system: resilience is necessary, but not sufficient for graceful degradation. However, the relationship is quite close; as mentioned above, the lack of an integrated conception, theory or model of resilience or graceful degradation across disciplines makes it impossible to state a clear, non-controversial relationship. One should conceive of this paper's conception as *axiomatic* within its context.

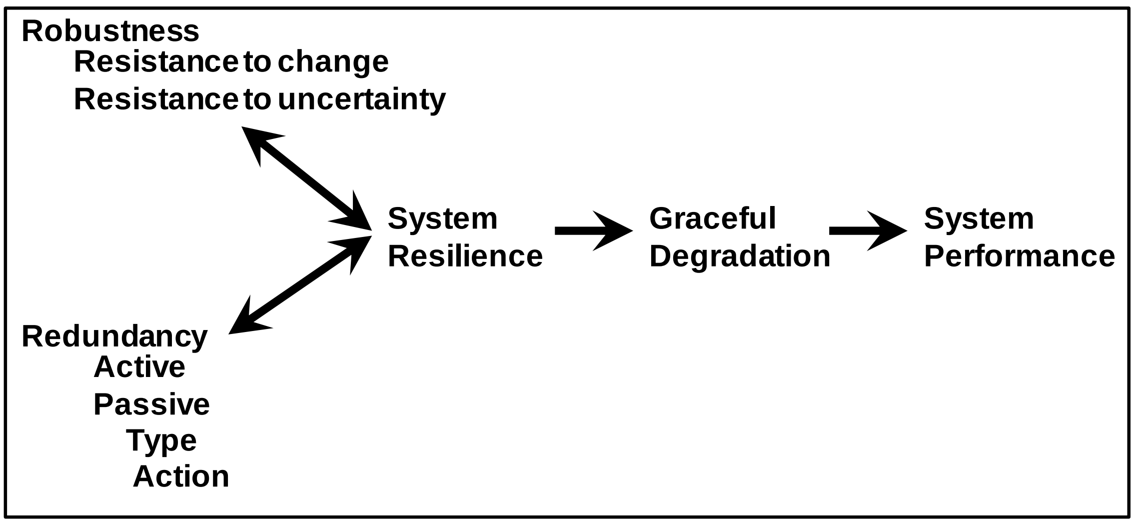

Figure 1: Relationship among Key Terms for Graceful Degradation

Robustness refers to the *strength* of a system. It can be expressed as a probabilistic resistance to failure across the possible system states: to changes from within and without the system, and to uncertainties associated with a system's several processes. Redundancy can be construed as the complement of robustness; it too refers to system strength, but in terms of a *multiplicity* of probable system operational capabilities, again across all possible system states.[3] Redundancy can be active or passive. Active redundancy occurs when there are more than one alternative system components that accomplish the same thing; the systems fails only when all components fail. For example, consider alternate communications means routing between military command centers, one possible alternate being via radio, another being via fiber optic or wire cable; messages can be passed across all means without overall communications system failure . Passive redundancy occurs when at least one backup system component exists ready to operate if primary capabilities fail, but is not operational. An example is

a homeowner's backup generator for use when public utilities are interrupted.[4] It is important to note the use of the term *probabilistic* in the discussion of resilience, robustness, redundancy, and graceful degradation. Uncertainties of occurance with unknown probability distributions inhabit the universe of complex adaptive systems (CAS), like command and control (C2) systems. In the following sections, oftentimes *probabilistic* is not explicitly used, but readers should understand that it is always meant.

The single overarching goal for applying the concepts of graceful degradation, fault-tolerance or resilience across all these fields is to achieve system sustainability – the ability of the system to meet current system demands without eroding the potential to meet future needs. The preponderance of 'best practices' have been based on a philosophy of optimizing a small subset of the components in the system in order to achieve the sustainable delivery of goods and services through the efficient use of resources. In the absence of applying a methodology such as Goldratt's Theory of Constraints[5], this optimization approach leads to the elimination of redundancies and aims to get a system into some particular 'optimal state' and then hold it there. This approach, however, leads to the paradoxical drastic loss of system resilience, making the total system more vulnerable to shocks and disturbances.[6]

All C2 systems have a common fundamental purpose: to sustain internal system cohesion in the presence of external environmental changes. This purpose requires all C2 systems to perform two activities: Command: directing a system to execute an iterative process of observing external changes, making sense of those changes, deciding how to adapt to those changes, implementing that adaptation, and then receiving feedback as to the effectiveness of the adaption and its impact on the environment: and, Control: regulate the critical internal processes of the system.

~~Our current military C2 systems have been designed to optimize a commander's ability to make decisions.~~ Throughout the remainder of the paper, we will describe the lessons learned in applying resilience, robustness, and redundancy from the various fields above and in the case studies as they relate to the three aspects of our C2 system: hardware (technology), software (doctrine, procedures), and the human integration of the two.

Graceful Degradation/Resilience by Applicable Domain

Of the various fields who have applied the concepts of graceful degradation or resilience, four have the most insights for applying these concepts to our C2 system. The four domains in increasing complexity are: materials engineering (engineering resilience), systems engineering (systems resilience), social-ecological system management (resilience in a CAS), and critical infrastructure management (resilience in a CAS with intentionally adversarial actors). Our C2 system will have aspects that best reflect one (or more) of these domains and any actions we might take to ensure graceful degradation should be informed by the insights from those domains.

Engineering Resilience

At the simplest individual component level, engineering resilience focuses resilience, redundancy, and robustness on a discrete part of a larger system. Resilience at this level is focused on designing the system to endure greater stress without becoming damaged, rapidly return to a normal condition, and "distort" less as a result of the stress – essentially to prevent or minimize change, avoid staying too long in the disruptive state and decrease the risk and severity of disturbances. At this level, resilience and robustness are essentially equivalent. Of critical importance when applying lessons learned from this domain is in understanding the underpinning assumptions: 1) there is only one equilibrium or normal state, 2) the object returns to this state after a disturbance it can handle, and 3) the type of disturbances are expected.[7] Redundancy at this level is concerned with the provision of functional capabilities that would not be necessary in a fault-free environment (duplication).[8] In addition to resilience, robustness and redundancy, being properties of individual machines within the system, it may also characterize the rules by which they interact. The means by which graceful degradation is achieved include: anticipating exceptional conditions and building the system to cope with them, aiming for self-stabilization, building in some form of duplication (redundancy), etc.

Systems Resilience

Within the systems engineering domain the focus is at the scale of groups of interacting agents – non-linear, dynamical systems. Even though these systems are deterministic – that is the behaviors of the agents in the system and their relationships to each other follow established rules which do not change – that does not mean these systems are predictable. These type systems can exhibit extremely complex behavior. What these systems lack is an ability to self-adapt and change.[9] Examples of this type system are the various human-designed infrastructure systems (communications, transportation, electrical, computer, etc.) with the human-in-the-loop removed. Since these systems do not exist as stand-alone systems (without any human interaction), a more detailed discussion of resilience, robustness and redundancy is better left to the next two domains of complexity.

Resilience in a Complex Adaptive System (CAS)

The next domain, social-ecological management, has been exploring the concepts of resilience for the last four decades as the result of many well publicized failures of well-intentioned traditional environmental management approaches. Resilience at this level is best defined as the ability of the system as a whole to withstand, recover from and still retain its basic function and structure or to reorganize in response to a crisis. The key feature of resilience in a CAS is the ability of that system to generate new ways of operating and new systemic relationships – its adaptive capacity.[10] The most significant aspect of a social-

ecological system that we must keep in mind in applying any lessons learned to a C2 system is the fact that all the "parts" of a social-ecological system are inherently adaptable – nature has already "built-in" a degree of resilience, robustness and redundancy. Not all parts of a C2 system have this "built-in" adaptability. Robustness at this level provides a level of physical and physiological tolerance to stress within the parts of the system that allows them to cope and survive, in a potentially degraded state, long enough to adapt to the stress. Robustness within the system as a whole can be achieved either: 1) by having redundant parts, where multiple components within the system have the same function; or, 2) through distributed robustness, where different components within the system having different functions, can still produce a comparable end-product.[11]

To this point, the discussions of resilience, robustness and redundancies have predominately pertained to the hardware and software aspects of a system. It is at this level where we first encounter the human integration of the two. One of the key features that changed in the transition from traditional environmental management approaches to those that embrace the concepts of resilience, was the recognition that humans are part of the system.[12] Human institutions and governance structures cannot be separated from the systems that they operate or manage; and, these institutions and governance structures are critical in promoting innovation which is critical for building resiliency.[13] The human component of any system provides the greatest source of adaptability and resilience.

<u>Resilience in an Adversarial CAS</u>

Another domain that has focused on resiliency has been disaster management. Within this domain, the 9-11 attacks in the United States added a threat to the natural hazards that had already been considered – that of intentional damage from the actions of an adversary, particularly to those infrastructure systems that are critical to support large urban areas. These infrastructure systems have evolved to become tightly coupled, complex systems where all of these systems influence each other establishing circular, reciprocal interdependencies – where a failure in one system causes failures in all other systems which in turn reinforce the failure in the original system.[14] Due to these relationships between critical infrastructure systems, a simple disturbance in one system can: 1) cause a failure in a second infrastructure system (a cascading failure); or, 2) exacerbate a disruption in a second system (an escalating failure).[15] Within this domain, the presence of an adversary requires an additional dimension be addressed within graceful degradation – that of protection.[16] Our C2 system reflects many of the aspects of this domain with the multiple interdependent infrastructure systems (e.g. satellites, communications, electrical systems, network management systems, intelligence collection systems, etc.), as well as, the presence of an adversary who is intentionally attempting to degrade our C2 capabilities.

Cases

All systems, including C2 systems, exhibit graceful degradation to a greater or lesser degree. This occurs by virtue of the interaction of all three aspects of their design: hardware (technology), software (doctrine, procedures, instructions), and the human interface between hardware and software producing system operations. In the following cases, therefore, though one aspect is emphasized over the others, the illustration is one of degree, not exclusion. In the world of systems, no one aspect or part can be understood without the context of all the others; they are interrelated.

Six cases of graceful degradation are presented in brief here. Each highlights one aspect of graceful degradation, either a successful or unsuccessful incorporation of graceful degradation, in the C2 system.

Case One: Successful Hardware Graceful Degradation

This is the case of the USS SAN FRANCISCO, described in the "Setting – A Historical Example" section of this paper. This ship was resilient to an extreme, taking unprecedented damage while both surviving its terrific battle at sea, and continuing to perform its primary function as a maritime weapons system of war – deliver naval surface fires in battle. The ship's command and control system had to survive in order to enable functioning; it did even though many of the humans (naval officers) in charge of the command and control system died during the battle. The command and control system was sufficiently robust to sustain significant damage to the ship's command and control center, the bridge, so that following a brief use of a passive redundant command and control system, the aft battle command center, the senior surviving officer was able to reassert command and control of the ship from the bridge. The ship's physical architecture had graceful degradation built into its design.

Case Two: Unsuccessful Hardware Graceful Degradation

The initial governmental effort to coordinate emergency efforts in the wake of Hurricane Katrina in 2005 provides the counter-case to the USS SAN FRANCISCO. So faulty were the C2 systems and efforts that the formal Congressional after action report dedicated an entire chapter to the failure.[17] Generally, there was a complete and catastrophic breakdown in communications between federal and state emergency operations centers and the local emergency operations centers in the affected areas of Katrina, primarily those in and around the city of New Orleans. The major reason for this failure was the inundation of the staging area for emergency electrical power, Army National Guard portable generators, located at the State National Guard's headquarters, Jackson Barracks. Apparently, no one in authority had considered the fact that the headquarters was situated in one of the lowest parts of the city. Once the levees were breached, the headquarters area was one of the first areas flooded. The primary planned capacity to provide emergency electrical power, which

enables the command and control system to continue to function, was compromised within the first hours of the crisis.

The emergency plans for C2 in the case of Katrina were sufficiently robust; there were plenty of emergency portable generators staged to New Orleans. However, staging them all at the headquarters, a critically vulnerable location, set up the entire command and control system for a single fault failure – in this case, flooding. There was little substantial active communication redundancy: cell phone towers had been flattened by the storm, telephone cables compromised by floodwaters, and only sporadic radio contact through a few commercial stations that had their own independent emergency power sources. The brittleness of the communications planning for Katrina coupled with a significant lack of redundancy meant that resilience of the C2 systems was low. Graceful degradation for local emergency operations centers in Louisiana during Hurricane Katrina was virtually nonexistent.[18]

Case Three: Successful Software Graceful Degradation

The illustration for this case is one of the latest historical examples of mission command, the Battle of Wanat, also known as the battle for Command Out-Post (COP) Kahler.[19] Mission command, derived from the old German C2 method *auftragstaktik*, radically decentralizes command authority to the lowest appropriate level, empowering even the most junior unit leaders to take the initiative, changing or even violating written orders, in consonance with the overall commander's expression of what he/she intended to happen.[20] Three unit conditions must exist for mission command to work: understanding, trust and intent.[21] When these conditions are met, and a mission command process is in place, C2 systems become extremely agile, often approaching "edge-like" qualities.[22] At the battle for Wanat, these conditions existed, and the result was a combat engagement in which a severely outmanned and outgunned American infantry unit successfully defended a very vulnerable combat outpost.

The American outpost at Wanat was at the end of a line of operation into the Waigul Valley in northeast Afghanistan. It was supposed to be a temporary location as American forces slowly consolidated their positions around the main population centers in the region; this consolidation was necessary due to the existing economy-of-force environment among allied forces throughout Afghanistan. An American infantry platoon, only two weeks from redeploying to its home station in the United States, drew the mission of establishing and initially manning this outpost. The location is shown in Figure 2 following:

Figure 2: Location of Outpost and Battle for Wanat

Though a temporary outpost, the negotiations with local tribal leaders had been ongoing for more than six months, thus allowing the enemy forces, primarily Taliban, to know where the outpost was specifically situated, and its configuration. The Taliban decided to use this intelligence to plan an assault on the outpost during its most vulnerable period, that of initial establishment.

The American unit, 2nd Platoon, C Company, 503rd Infantry (ABN), with Afghan Army reinforcements had approximately 75 soldiers, led by a 1st Lieutenant Jonathan Brostrom. Also on hand was his company commander, Captain Matthew Myer. In the early hours of 13 July 2008, between 200 and 500 enemy combatants assaulted the outpost. Though nine (9) soldiers died, including Brostrom, and forty-seven (47) were wounded, the unit held the outpost.

There are two schools of thought on why the outmanned American and Afghan unit was able to repel the attack. One line of thinking focuses on the tactical incompetence of the attackers: though they had the elements of surprise and overwhelming numbers, their proficiency with arms and coordinated action were lacking.[23] This interpretation understates the role of the American soldiers involved in the combat.

The second line of thinking on the battle, captured in the Combat Studies Institute report on the engagement, points to the doctrine, discipline, and courage of the unit and soldiers involved in the battle. Even though the formal C2 personnel of the unit were killed or wounded, others immediately stepped into their place and continued the defense; this behavior is consistent with U.S. Army training doctrine. Through the soldiers' high level of training, the robustness of the C2 system enabled the unit to perform under most distressing circumstances. Also, the active and passive redundancy inherent in decentralized C2 – in this case, individual soldiers – reinforced the system's

robustness. What resulted was an extremely resilient C2 system that was able to accept extreme damage (over 80% unit casualties), and still function.

Case 4: Unsuccessful Software Graceful Degradation

> *"No one knows exactly what is going on."* Message from Headquarters, First Army to Headquarters, Northeastern Front, 13 May 1940[24]

The converse of mission command is positive C2. This form of C2 works well with situations and environments that are well understood, and relatively constant; for example, assembly lines in factories. In these environments, C2 systems doctrine assumes security and reliability; they are sufficiently robust. Risk of C2 systems failure shifts to redundancy and resilience: because both these characteristics require resource investments not directly associated with outputs, the necessary doctrine guiding implementation of C2 hardware is not in place. The C2 system becomes, in a word, brittle.[25] If positive C2 systems are applied to conditions outside the parameters for which they are designed, the opportunity for catastrophic system failure becomes not only possible, but probable. This is the case of the Allied response to the German invasion of France in April, 1940, Operation *Fall Gelb*.

The facts of the *Fall Gelb* are well known and well documented.[26] The Germans took advantage of an Allied oversight of the operational situation, the assumption that armored forces could not be employed in the heavy forested region of the Ardennes, Belgium; they used this advantage to impose a pace of operational action that completely mystified the Allied high command. Allied commanders and their staffs could not keep up with critical events and actions happening across their front. The result was a complete victory for the Germans and an unexpected catastrophic defeat for the Allies (and a complete defeat for the French.) Undeniably, the origin of German victory is the operational and tactical surprise that they achieved, particularly in the most vulnerable part of the front, that part of France, including the city of Sedan, facing the Ardennes. Beyond that, though the German victory can reasonably be argued to be one of arms, the reality was that Germans first defeated the Allied C2 systems, forcing a brittle C2 system to unsuccessfully adapt when its doctrine of positive centralized C2 attempted to enable Allied High Command to impose its presence on a fluid battlefield environment. Then the Germans took advantage of the ensuing confusion to force the decision through fast-paced actions.

Allied C2 systems doctrine worked quite differently from the Germans. Allied High Command, physically situated a significant distance from front lines (from Headquarters in Paris to Sedan is about 100 miles as the crow flies), called for centralized C2 exerted over an apparently robust system of telephone and telegraph lines through Fronts to Armies to Corps to Divisions.[27] Allied C2 systems applied redundancy in means through use of messengers (both human and pigeon.)[28] Radio communications was scarce. It appeared that the Allies

envisioned a war moving at a pace similar to the First World War, in which units and front lines moved only in small increments, except for the last three months of that war.[29] If the pace of operations were like that of WW1 then the Allied C2 doctrine might have had a chance of working. Instead, the Germans practiced an asymmetric form of the rapid offensive, concentrating their mobile forces against the least mobile Allied (French) forces, attacking relentlessly, disrupting Allied lines of communications and operations without regards to their own flanks, causing uncertainty, paralysis, mayhem and eventually hopelessness within Allied Command.[30] Allied C2 doctrine simply was non-adaptive, and broke under the stress of enemy pressure.

Case 5: Successful Human Graceful Degradation

In the environment of military C2, the commander and his/her staff is the central element in the organizational CAS. How they cope with unexpected and even unanticipated situations often determines the fate of armies. Successful coping or adaptation in these crisis environments is synonymous with successful human graceful degradation. Commanders and their staffs must sense, think, decide and direct actions within organizational systems that are at least partially compromised and dysfunctional; they must so behave, accomplishing their C2 tasks despite failures of key components of their sensing, communications, and information processing sub-systems. One exemplary illustration of this capability is the case of RADM Clifton Sprague, commander of Task Group 77.3, at the Battle off Samar, an engagement of the larger battle of Leyte Gulf, 25 October 1944.

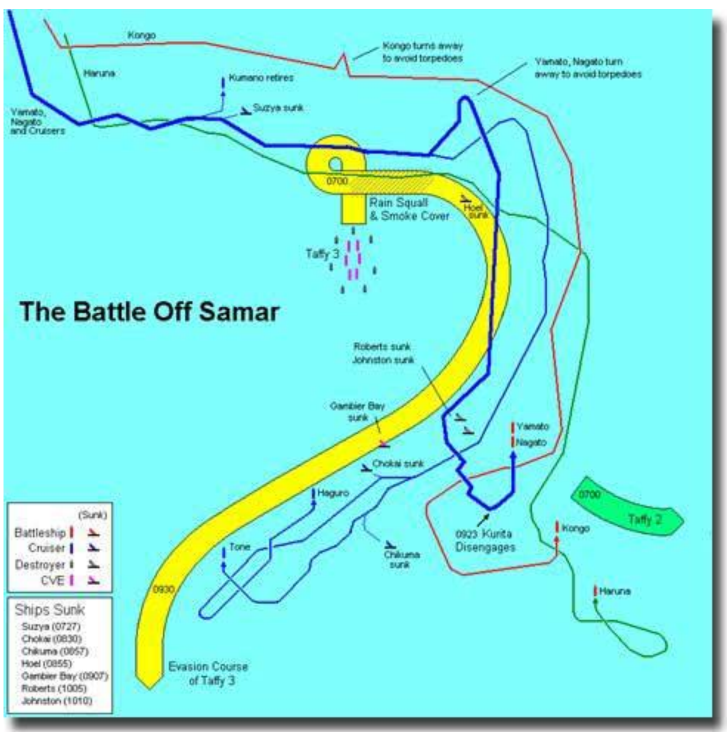

Figure 3: The Battle off Samar

At 0645 hours on October 25, 1944, RADM Sprague and his staff looked forward to a typical morning of flight operations to be executed by his task group, one small element of the 7th Fleet, supporting the American amphibious landings on Leyte, the Philippines.[31] Two earlier naval battles had occurred during the day on the 24th: one in the Sibuyan Sea to the west of Leyte in which naval aircraft from ADM William Halsey's powerful 3rd Fleet had attacked a major Japanese surface force commanded by ADM Kurita; the second fought between surface elements of the 7th Fleet under VADM Oldendorf and Japanese forces under ADM Nishimura in the early hours of the 25th in Surigao Strait resulted in the almost complete annihilation of the Japanese fleet. To Sprague it looked like the Japanese effort to disrupt the landings had failed. Halsey's fleet now was off pursuing a Japanese carrier force far to the north; everywhere the Japanese navy appeared to be in retreat. What he and his sailors did not know was that after the Sibuyan Sea engagement, Admiral Kurita had reversed course during the night, turning what appeared to U.S. naval aviators as a retreat into a quick debouchment from the San Bernadino Strait and directly into the path of Sprague's little task group. Sprague and the rest of 7th Fleet had expected ADM Halsey to provide a protective cover against just such a possibility; however, Halsey practiced the principle of mass and took his covering force with him in pursuit of the Japanese carriers.[32] The Americans had six small escort carriers (top speed 19 knots) with seven destroyers and destroyer escorts as protection for the carriers; the Japanese had four battleships, six heavy and two light cruisers, and eleven destroyers (overall Japanese fleet average top speed 28 knots.)

At 0646 hours, the forces made contact, first through an aerial sighting by one of the escort carrier pilots followed almost immediately by lookouts on both sides. Between this moment and time and approximately 0700 hours, RADM Sprague would make no less than four major decisions, exercising personal and direct C2 over his small and terrifically outgunned force; all the decisions he made were the best possible under the circumstances. All worked to his advantage. First, Sprague ordered his entire force to turn into the wind, with covering destroyers taking the flank nearest the Japanese. He then proceeded to commence an immediate launch of all available aircraft – no matter what armaments they were covering – and for those air assets to attack the Japanese force. He also recalled previously committed air assets from supporting ground forces on Leyte and conducting anti-submarine patrols, ordering them to attack the enemy with whatever weapons they carried. Sprague adjusted his maneuver to seek a nearby rain squall to further provide some natural cover for his force; to give his force time to get to the squall, he ordered his covering force to lay down a smokescreen; this worked well. Sprague had his staff broadcast a critically urgent call for help on all available radio channels – in the clear in order to save time associated with encryption. Finally, he ordered his covering force to attack the enemy, a maneuver that his screen executed with extreme aggressiveness. As his biographer would observe, "He disregarded no tactic, no

matter how hopeless it might appear… He utilized his interior lines. He maneuvered through his own smoke… He ordered his carriers to zigzag and to chase enemy shell splashes…"[33] All these actions bought his force about ninety minutes of time; but, by 0900 the Japanese, who had commenced firing at range shortly after sighting Sprague's ships (mistaking them for a task force of the 3^{rd} Fleet), had significantly closed the range, thus improving the accuracy of their fire; his screen was decimated and the enemy shells started hitting his carriers. USS GAMBIER BAY was the first carrier to get hit and eventually sunk by the Japanese. Yet, less than fifteen minutes later, ADM Kurita turned his force away from Sprague, and headed north. The little Task Group 77.3 somehow had survived a massive naval assault and had retained control of their part of the sea. The reasons for the Japanese retreat have been discussed over the decades since the battle;[34] here the focus is on Sprague's decision-making as the key part of the C2 system.

Clifton Sprague adapted his command to surmount circumstances for which his force had no reason to train for or to expect to experience. His decision cycle was exceptionally quick – most significant, it was far quicker than his opponent's. Of interest is that he also retained control of his forces throughout this chaotic affair; the Japanese leadership did not – Kurita had allowed a "general pursuit" in which every Japanese ship could take whatever action necessary to close with and destroy the enemy. Sprague demonstrated a resilience and spirit of adaptation in command that commends his actions to all would-be admirals of the ocean sea. How he achieved such a personal C2 capability is unremarkable:~~;~~ he trained for this kind of command and exercised it repeatedly over his naval career. Indeed, it was his ship, USS TANGIER, that fired the opening American shots of the Pacific war at Pearl Harbor, three years before the Leyte action; he had trained his staff and crew to expect the unexpected; when that happened, specifically in the instance off Samar that morning in October, 1944, the right commander for the right situation was in right place.

Case 6: Unsuccessful Human Graceful Degradation

Albert Einstein supposedly provided a definition of insanity: doing the same thing over and over again and expecting different results. When organizations, as well as individuals, fail to adapt to their environment, their repeated efforts to continue their normal way of doing things, invariably leading to catastrophe, constitutes the case of unsuccessful human graceful degradation. Leadership in these unfortunate organizations has lost resilience, and fixes on the present means in a vain effort to force a desirable future. This is the case of Lieutenant General (LTG) Courtney Hodges, commander of 1^{st} Army, European Theater of Operations, and his subordinate commanders at the Huertgen Forest campaign, September 1944-January 1945.

Figure 4: The Huertgen Forest

The Huertgen Forest battle was the longest ground engagement fought in the European Theater of Operations (ETO).[35] It involved no less than 120,000 soldiers on the American side, of whom over 31,000 became casualties (including over 6,800 battle deaths.) Of the five divisions that eventually participated in the battle, two were rendered *hors d' combat*, ~~rendered~~ ineffective due to excessive casualties. On average, there were 5,000 casualties per division (authorized division strength approximately 17,000.) Many infantry regiments suffered in excess of 100% casualties over the duration of the fight. Yet, the battle effectively led to nowhere, and even the official history describes the purpose as one merely of attrition.[36] That was not what First Army expected.

The initial reasons for the Huertgen Forest battle were reasonable. The Allied ground forces in the ETO were pursuing the retreating Germans at a rapid pace with little concern about flanks or reinforcing lines during August and early September, 1944. This meant that ground forces were scattered with fronts far wider than what normally they would hold in less mobile times; this was and is an essential characteristic of maneuver warfare. However, when the Allies approached Germany, they ran into a long fortified line of German defenses, known as the *Westwall* to the Germans and the Siegfried Line to the Allies. At first, the Allies, and First Army in particular, assaulted this line in their spread formation. LTG Hodges and his staff focused on a generally West-East line from Aachen to Duren as a direct path through the Siegfried Line; this was the so-called "Stolberg Corridor." Just to the south of this axis of advance was the

Heurtgen Forest; in the interest of protecting the flank of the main effort, Hodges directed that one infantry division, the 9th, clear the forest and secure the north-south roads that the Germans could use to move units to bolster defenses. The first problem for the 9th Division was that held a front normally twice as wide as it doctrinally should have held, encompassing almost the entire forest. The second problem was that First Army had given the division several other missions in addition to the clearing operation, including a main effort along the Corridor; the unit could not concentrate its combat power on just one thing.[37] The physical ground of the forest provided~~s~~ a formidable foe in itself; the forest was ~~is~~ dense cut with extremely steep gorges ~~cut~~created by small creeks and rivers. The Germans held the high ground and had pre-registered the area with artillery; they also had hundreds of concrete "pillbox" fortifications. Attackers had to move slowly through the terrain, without much friendly armor, artillery or close air support (a decisive Allied capability), against an entrenched foe. The result was a bloody repulse that left two of the three regiments of the division combat ineffective~~in tatters~~. If, at this point, LTG Hodges, his staff, and his subordinate commanders had learned a lesson from this rebuff and not continued their efforts, historians may have written this first battle as an unfortunate footnote to a deadly conflict. That was not what happened.

The main First Army assault through the Stolberg Corridor bogged down due to significant German resistance. General Hodges and his staff began looking to the Huertgen Forest as a flank attack to take pressure off the main effort immediately to the north in the Corridor. Once again they chose a division, the 28th, to attack in a southeasterly direction towards the town of Schmidt, near the southeastern end of the forest.[38] The direction of the assault would force the division through the densest and most difficult terrain of the forest, without any transportation lines of communication; indeed, the division would have to build its own supply road~~trail~~, the infamous Kall Trail, to enable a line of communications from the front. The division's main axis of advance, including the supply road, was completely covered by German artillery. Equally important, V Corps, responsible for the planning of the attack, gave the Division three distinct objectives that faced in three different direction; once again, a division could not mass its combat power to achieve the main objective – the town of Schmidt.[39] By this time, about two weeks after the 9th Division's experience, the Germans had moved reinforcements into the forest; thus, with approximately the same firepower as the 9th applied (two regiments), the 28th Division had to assault into the worst part of the forest in which the enemy had essentially doubled its defensive capabilities. The resulting attack, taking place over fourteen days, was repulsed with extremely heavy casualties; one regiment effectively ceased to exist. Still First Army leadership remained undaunted. It replaced the battered 28th Division with the 4th Infantry Division, and gave it the same mission, again with the same divergent tasks. In this case, though, the 4th received help from the 8th Infantry Division. LTG Hodges had recognized that one division was insufficient to manage the Huertgen; the 8th was to attack

parallel and south of the 4th. Unfortunately, the result was only mildly different; the 4th was able to advance to some high ground in the eastern part of the forest; the 8th was to reach the approaches and high ground overlooking~~f~~ Schmidt, taken and lost by the 28th more than three weeks earlier.[40]

During these two months of intense combat, none of the First Army leadership or planners visited the terrain into which they were sending divisions. Equally astonishing, it seems that the Corps commanders (MG Gerow of V Corps and MG Collins of VII Corps), who held the responsibility for detailed planning of the attacks, also did not reconnoiter the terrain.[41] The human C2 system had virtually no situational awareness of the operational environment. General Hodges and First Army headquarters held the responsibility to frame the operational picture in which his corps and division units would operate; he personally approved all plans; he was responsible to provide the commander's intent for his subordinates to execute. ~~First Army also had the major support responsibility for fighting units.~~ The framing lacked situational understanding; the plans were faulty and failed in the extreme; Hodges never truly provided a good reason for the entire effort.[42] Instead of learning from what had happened to his units, Hodges merely reinforced failure, almost as an autonomic reflex – the enemy is there, go fight them. What was worse is that he micro-managed his army, and held his subordinate commanders on short leash; this led to subordinate commanders watching over their shoulders, and providing overly optimistic situation reports to get the higher headquarters off their backs.[43] This poisonous C2 atmosphere resulted in no one questioning the reason for attacking into the Huertgen Forest when other options (flanking and blocking maneuvers) were available; only in mid-December did one senior leader, MG James Gavin, acting commander of XVIII Airborne Corps, actually visit the battlefield, witness the carnage, and return to First Army headquarters, asking the question: why attack into the Huertgen in the first place? He never received an answer.[44]

Observations and Recommendations

This paper has introduced the concept of graceful degradation to the command and control discipline; it is the ability of a system to continue functioning even in face of critical sub-systems/component failure or malfunction. It has developed the concept based on resilience, which itself is based on redundancy and robustness. The paper has discussed several and diverse schools of thought on resilience which in turn is directly and strongly correlated with graceful degradation. It presented six cases of the three fundamental aspects of a command and control system (hardware, software, humanware): three successful and three unsuccessful.

Based on the review of the different domains as well as the case studies, the authors provide the following overarching considerations in applying resilience thinking as a means for achieving graceful degradation. These considerations will require ~~is~~ continuall~~y~~ analysis and assessment~~zed~~ for improved design characteristic and capabilities within our organizational and

technological C2 systems, as well as, inculcating the concepts into the minds of current and future leaders. One can understand these considerations as guidelines for a research program on graceful degradation in C2 systems.

- **Resilience requires trade-offs** (these tradeoffs can either occur within one particular system or across different systems within a family of systems) and increases near-term "costs"[45]
    - Increasing resilience at one level of the system can decrease resilience at another level
    - Increasing resilience in one system aspect can decrease resilience in another system aspect
    - Increasing resilience (through redundancy) implies *decreased* efficiency (e.g. increased costs without commensurate short-term opportunity gains)
- **Resilience requires change**; a system needs to experience a shock or perturbation (which can be simulated rather than actual) in order to learn and adapt. Methods that attempt to prevent all crises, to sustain a system in the short-term, can decrease resilience in the long term.[46] However, it is just as important have methods that prevent large, catastrophic shocks that would result in the system being unable to accomplish its mission. Historically, the military has implemented a number of practices to achieve graceful degradation for operations in persistent and non-persistent chemical environments and for operations with limited communications capability (either deliberate or consequential). These techniques ranged from developing the expectations and rules of thumb for operating tempo slow-downs; training and rehearsals in the form of individual soldier tasks, unit tasks, and larger exercises; to the use radio silence and signal operating instructions.[47] Additionally, in response to the Soviet threat in the 1970's/1980's, each Service established training environments (the Army's National Training Center, the Air Force's Red Flag, and the Navy's Top Gun) that sought to present extremely difficult tactical and operational challenges to military forces in order for them to learn, adapt, and increase their resilience. These environments parallel similar efforts undertaken by the military during the interwar years (between WWI and WWII) such as the Naval War College Rainbow Wargames and the Louisiana Maneuvers.
- **Resilience requires an acceptance of unpredictability.** As we alluded to earlier, CAS behaviors and environments cannot be fully predicted or even completely understood; therefore, managing for resilience requires that we understand and accept the inherent "unknowability" of our system. Uncertainty is a fundamental limitation to how much we can understand about our world.[48] Accepting

uncertainty, however, does not imply abdicating a responsibility to reduce the "unknown-unknowns" (by increasing: 1) the "known-knowns" – those things that we know, we know; 2) the "known-unknowns" – those things that we know, we do not know; and 3) the "unknown-knowns" – those things that we knew previously but have forgotten and those things that we know, but are unaware that we know). Focusing on general resilience – the ability of a system to absorb unforeseen disturbances – allows a system to be designed for exapation (creating systems and processes which allow things to come together in radical and novel ways).[49]

- **Increased resilience is dependent upon selecting actions that are informed by the existing system state**: the same action can increase or decrease resilience based on the state of the system.Resilience requires leaders and managers in the system to *focus on coping mechanisms* rather than optimizing mechanisms.[50] General Dempsey, in his "Mission Command White Paper" advocates for the military to train commanders on how to avoid information overload and "paralysis by analysis" and to allow the commander to rehearse making rapid decisions without perfect or complete information.[51]
  Since any disturbance or change can lead to increased resilience, then any action taken to "disturb" an adversary could ***increase*** their resilience and ***decrease*** our own resilience.
- **Resilience requires a culture** that:
  - Allows a variety of leadership styles and multiple leadership roles vested in different individuals
  - Fosters a high degree of trust (up and down as well as laterally) and a requirement to know the mission partners – their authorities, decision-making culture, and how they communicate[52]
  - Uses decision making processes and criteria that seek to retain all options open[53]; to having alternatives, the ability to grab an emergent opportunity.
  - Provides the capacity and capability to self-organize and reorganize, i.e. to move around different classes of C2 approach: Edge C2, Collaborative C2, Coordinated C2, De-Conflicted C2, and Conflicted C2[54]

In the recently published Capstone Concept for Joint Operations: Joint Force 2020, the United States Joint Chiefs of Staff articulate the requirement for a commitment to the use of mission command as the most appropriate command philosophy to empower decentralized subordinate leaders to exercise judgment in their actions to advance the commander's intent.[55] This same document recognizes that mission command may not be appropriate for all situations and

that each of the Services implement different versions of mission command. As a result, this document provides six implications with respect to C2 and two implications with respect to intelligence. Embedded within these eight implications lay ideas that would support graceful degradation such as: educating commanders and staffs to match command philosophy to the particular requirements of each mission, regularly training the force to operate in "worst case" degraded environments, making a common set of command and control applications available as cloud services, building greater resilience into technical architectures, developing capabilities and tradecraft that provide broader intelligence to decision makers, and improving the capabilities that fuse, analyze, and exploit large data sets.[56] Each of these ideas supports the adoption of graceful degradation as a C2 virtue; together, they address the key issues revealed from the six cases of hardware, software, and "humanware" aspects. What remains is the extent to which the ideas are translated into programs, and the programs in turn converted to reality.

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[1] The full account of the First Naval Battle of Guadalcanal, including the *via dolorosa* of the USS San Francisco, can be found most histories of the Guadalcanal campaign. The reference for this version is James D. Hornfischer, *Neptune's Inferno*, Bantam Books, New York, 2011, 282-316.

[2] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 2-5, 43.

[3] A formal mathematical relationship between these two concepts can be found in K. Zhia, "Redundancy and Robustness of systems of events," *Probabilistic Engineering Mechanics* (2000), 15, 347-357.

[4] The concepts of active and passive redundancy have no standard definition, as can easily be garnered from a quick search on the Internet. Here, the referenced terms are mathematically defined, as found in Harvey J. Greenberg, " An Application of a Lagrangian Penalty Function to Obtain Optimal Redundancy," *Technometrics*, Vol. 12, No.3, August, 1970, 545-552.

[5] Goldratt Institute, "The Theory of Constraints and its Thinking Processes", 2009, http://www.goldratt.com/pdfs/toctpwp.pdf; and Mabin, Victoria, "Goldratt's 'Theory of Contraints' Thinking Processes: A Systems Methodology linking Soft with Hard", http://www.systemdynamics.org/conferences/1999/PAPERS/PARA104.PDF.

[6] Walker, Brian and David Salt, *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*, Island Press, Washington, DC, 2006, pg. 5-9.

[7] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 5-6, 43.

[8] National Institute of Standards and Technology, *A Conceptual Framework for System Fault Tolerance*, http://hissa.nist.gov/chissa/SEI_Framework/framework_1.html, 30 Mar 1995, accessed on Jan 23, 2013.

[9] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 6, 45-46.

[10] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 7.

[11] M-A Felix and A. Wagner, "Robustness and evolution: concepts, insights and challenges from a developmental model system", *Heredity* (2008) 100, 132-140, published online 13 December 2006.

[12] Walker, Brian and David Salt, *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*, Island Press, Washington, DC, 2006, pg. 31-32.

[13] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 17.

[14] T.D. O'Rourke, "Critical Infrastructure, Interdependencies, and Resilience", *The Bridge*, National Academy of Engineering, Vol. 37, No. 1, Spring 2007.

[15] Richard Little, "Toward More Robust Infrastructure: Observations on Improving the Resilience and Reliability of Critical Systems", Proceedings of the 36th Hawaii International Conference on System Sciences, 2002.

[16] John D. Moteff, "Critical Infrastructure Resilience: The Evolution of Policy and Programs and Issues for Congress", Congressional Research Service, August 23. 2012.

[17] The report, produced by the U.S. House of Representatives Special Bipartisan Committee, was *A Failure of Initiative: Final Report of the Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina*, U.S. Government Printing Office, 2006, 183-198.

[18] Ibid. For a short list of what happened, consult the Summary, 183-184.

[19] The source for this case has been significantly edited in its final form by the Combat Studies Institute, Ft. Leavenworth, Kansas. However, one of the authors of this paper had the opportunity to save the final draft before editing, thus preserving a great deal of information about the performance of command and control during the battle. Popularly known as the "Cubbison Draft," a more formal citation would be as follows. Douglas R. Cubbison, *The Battle of Wanat*, (Final Draft), Combat Studies Institute, Ft. Leavenworth, Kansas, 2009.

[20] Joint Chiefs of Staff, *Mission Command White Paper*, Washington, D.C., 3 April 2012, 3-4.

[21] Ibid., 4-5.

[22] The term, edge organization, refers to a specific organizational form characterized by a very high degree of information sharing and information generation among all members of the organization, coupled with a highly "flat" command structure. See for a detailed discussion of these organizations, David S. Alberts and R.E. Hayes, *Power to the Edge*, CCRP Publications, Washington, D.C., 2003.

[23] See Randall Steeb, John Matsumura, Thomas J. Herbert, John Gordon IV, and William W. Horn, *Perspective on the Battle of Wanat*, Rand Corporation, Santa Monica, California, 2011, 18-19.

[24] From Ernest May, Strange Victory: Hitler's Conquest of France; New York: Hill and Wang, 2000, 415.

[25] The concept of brittle C2 systems here is borrowed from the materials science discipline. Thus, one should understand the use of the concept as metaphor or analogue, not the thing itself. An excellent fairly comprehensive introduction to brittle systems can be found in Stephen F. Bush, John Hershey, and Kirby Vosburgh, "Brittle System Analysis," KWC-512, General Electric Corporate Research and Development, Once Research Circle, Niskayuna, New York, 1999, 1-13.

[26] Two summaries of this campaign are worth one's efforts. First, there is Ernest May, Strange Victory…. An older but popular history is Alistair Horne, To Lose A Battle: France 1940; New York, Penguin Books, 2007.

[27] This hierarchy of command was similar to the Germans in structure, but not behavior. The Allies insisted on a positive C2 doctrine from top to bottom; the Germans, of course, practiced their mix of *auftragstaktik* and *befehlstaktik* allowing for individual subordinate command initiative if the situation warranted. For French and Allied C2 doctrine consult Elizabeth Kier, Imagining War: French and British Military Doctrine Between the Wars; Princeton, New Jersey: Princeton University Press, 1999. For German C2 doctrine, consult Robert M. Citino, The German Way of War: From the Thirty Years War to the Third Reich; Lawrence, Kansas: University of Kansas Press, 2008.

[28] German air attacks against Allied lines of communication disrupted telephone and telegraph traffic. Refugee streams caused delays of human messengers. There are no official assessments of the effectiveness of pigeon messengers. Allied senior commanders had to drive (the Allies lost command of the air) to sense what was happening to their front lines, thus placing themselves out of communications – a most dangerous situation when practicing positive C2. Read J.E. Kaufmann and H.W. Kaufmann, Hitler's Blitzkrieg Campaigns: The Invasion and Defense of Western Europe, 1939-1940; Conshohocken, Pennsylvania: Combined Books Inc., 1993, Chapter V.

[29] Among others, Gerhard L. Weinberg makes this observation in his magisterial A World At Arms: A Global History of World War II; Cambridge: Cambridge University Press, 1994, 127-128.

[30] Though by no means assured or as perfect as some military historians have written, the German effort made up for its mistakes through relentless activity that gave the Allies no chance to re-orient, to make sense of what was happening to them. Among the exceptional military recitations of this campaign, the newly translated official German version of events, edited by Klaus A. Maier, Horst Rohde, Bernd Stegemann, and Hans Umbreit, Germany and the Second World War: Volume II Germany's Initial Conquests in Europe; Oxford: Clarendon Press, 2003, Part VI, Chapter 5 stands out as concise and complete.

[31] The following discussion is based on the description of the action and RADM Sprague's vital contribution can be found in John F. Wukovits, Devotion to Duty: A Biography of Admiral Clifton A. F. Sprague; Annapolis, Maryland: Naval Institute Press, 1995, especially Chapter 10-11.

[32] The Japanese carrier force was a decoy meant to lure Halsey's 3rd Fleet away from the Leyte landing area. In doing so, the Japanese surface forces would converge from the north (through San Bernadino Strait) and the south (through Surigao Strait) to raise havoc with the amphibious operations ongoing in Leyte Gulf. Kurita did not know that the Southern Force had been annihilated the night before his entrance. Halsey fell for the bait. Of the many informative histories of the Leyte Gulf battle, one of the oldest still remains excellent: read Samuel Elliot Morrison's History of United States Naval Operations in World War II, Leyte, Volume 12, June 1944-January 1945; Secaucus, New Jersey: Castle Books, 2001.

[33] Wukovits, Devotion to Duty, 160.

[34] Kurita survived the war and had interviews with American intelligence. The aggressive attacks of naval air coupled with the aggressive maneuvers of Sprague's screen created a sense of confusion in his mind – a case of the infamous fog of war. He also insisted he received a message from Japanese Navy headquarters indicating that Halsey's 3rd Fleet was returning (it had not); no other staff officer of the good admiral could recall such a message. Read Morrison, History… 296.

[35] This battle generates a great deal of emotion among those who have written about it; from what can be gathered in reading the memoirs and unit histories, frustration, fear, anger, hopelessness and sadness were pervasive feelings among those who fought there. Ernest Hemingway, who visited the battlefield as a correspondent, wrote a dramatic and pathetic description of the scene in his Across The River and Into The Trees; New York: Scribners, 1998. The numbers associated with the battle originate from Charles B. MacDonald, The Siegfried Line Campaign; Washington, D.C: U.S. Government Printing Office, 1993, 493.

[36] Ibid.

[37] Ibid, 83-86.

[38] An exceptionally readable, although somewhat polemical, history of the 28th Division's time in the Huertgen Forest – and the main source for this paper's description of the division's time – can be found in Cecil B. Curry's Follow Me and Die: The Destruction of an American Division in World War II; New York: Military Heritage Press, 1984.

[39] Ibid, Chapter 2.

[40] The most successful 4th ID regiment was the 22nd Infantry which lost 86 percent of its starting force including all three infantry battalion commanders over a three day period. Overall, it suffered an amazing 140 percent casualties during its fight in the Heurtgen. Consult Robert Sterling Rush's excellent Hell in Huertgen Forest: The Ordeal and Triumph of an American Infantry Regiment; Lawrence, Kansas: University of Kansas Press, 2001.

[41] Curry, Follow Me…, 262. Also consult Charles Whiting's vituperous The Battle of Hurtgen Forest; Conshocken, Pennsylvania: Combined Publishing, 2000, 166-167.

[42] Williamson Murray and Allan R. Millett, A War To Be Won: Fighting The Second World War; Cambridge, Massachusetts: The Belknap Press, 2000, 461.

[43] Hodges' leadership style is well documented in David W. Hogan, Jr. A Command Post at War: First Army Headquarters in Europe, 1943-1945; Washington, D.C.: Center For Military History, United States Army, 2000, 185-187.

[44] The Gavin episode is recorded in several histories, including those mentioned above. Here the reference is from his biography by T. Michael Booth and Duncan Spencer, Paratrooper: The Life and Times of GEN. James M. Gavin; New York: Simon & Schuster, 1994, 279.

[45] Dr, Brian Walker; "Learning how to change in order not to change: Lessons from ecology for an uncertain world,"; Krebs Lecture 2012, February 20, 2012; Goldratt Institute, "The Theory of Constraints and its Thinking Processes", 2009, http://www.goldratt.com/pdfs/toctpwp.pdf; and Mabin, Victoria, "Goldratt's 'Theory of Contraints' Thinking Processes: A Systems Methodology linking Soft with Hard", http://www.systemdynamics.org/conferences/1999/PAPERS/PARA104.PDF.

[46] Dr, Brian Walker; "Learning how to change in order not to change: Lessons from ecology for an uncertain world,"; Krebs Lecture 2012, February 20, 2012, http://www.canberra.edu.au/centres/iae/lectures/iae-krebs-lecture-2012-high.php and Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 50-51.

[47] Lanham, Michael J., Lt. Col., "When The Network Dies", Armed Forces Journal, December 2012, pg. 11-13.

[48] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg 50-51.

[49] Snowden, Dave, Keynote Speaker at XP2012 in Malmo, Sweden, May 21-25, 2012, http://www.youtube.com/watch?v=yXlePVkTY0A and http://www.youtube.com/watch?v=KanNaOqmli4.

[50] Martin-Breen, Patrick and J. Marty Anderies, *Resilience: A Literature Review*, Rockefeller Foundation, September 18, 2011, pg. 49.

[51] Dempsey, Martin, General; Mission Command White Paper, 3 April 2012.

[52] Luck, Gary, General (Retired), *Mission Command and Cross-Domain Synergy*, March 2013, Deployable Training Division of the Joint Staff J7, pg. 2-7.

[53] Martin, Roger, *The Opposable Mind: Winning Through Integrative Thinking*, Harvard Business Press, Boston, Massachusetts, 2009.

[54] Alberts, Dr. David S., Reiner K. Huber, and James Moffat, *NATO NEC C2 Maturity Model*, DoD Command and Control Research Program, February 2010, pg. 65-66.

[55] Joint Chiefs of Staff, *Capstone Concept for Joint Operations: Joint Force 2020*, 10 September 2012, pg. 4-5.

[56] Joint Chiefs of Staff, *Capstone Concept for Joint Operations: Joint Force 2020*, 10 September 2012, pg. 8-10.

Graceful Degradation: A C2 Design Virtue for Our Times
ICCRTS Paper #3

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Key Terms for Graceful Degradation

Graceful degradation occurs by virtue of the interaction of 3 aspects of system design

1. Hardware (Technology)
2. Software (Doctrine, procedures, instructions)
3. The human interface between hardware & software

Robustness

- **Resistance to change**
- **Resistance to uncertainty**

System Resilience → **Graceful Degradation** → **System Performance**

Redundancy

- **Active**
- **Passive**
- **Type**
- **Action**

Key Terms for Graceful Degradation

Robustness

Resistance to change

Resistance to uncertainty

System Resilience → Graceful Degradation → System Performance

The ability of a system to perform a specified function

Redundancy

Active

Passive

Type

Action

Key Terms for Graceful Degradation

Robustness
- Resistance to change
- Resistance to uncertainty

The properties that enable a system to continue operating in the event of the failure in some of its components

System Resilience → **Graceful Degradation** → **System Performance**

Redundancy
- Active
- Passive
  - Type
  - Action

Key Terms for Graceful Degradation

Robustness
Resistance to change
Resistance to uncertainty

System Resilience → Graceful Degradation → System Performance

The ability of a system to tolerate stress

Redundancy
Active
Passive
Type
Action

Key Terms for Graceful Degradation

The *strength* of a system:
- Ability to resist changes from both in/out
- Ability to resist the uncertainties associated with system processes

Robustness
- **Resistance to change**
- **Resistance to uncertainty**

System Resilience → **Graceful Degradation** → **System Performance**

Redundancy
- **Active**
- **Passive**
  - **Type**
  - **Action**

Key Terms for Graceful Degradation

Robustness

- **Resistance to change**
- **Resistance to uncertainty**

System Resilience → **Graceful Degradation** → **System Performance**

Redundancy

- **Active**
- **Passive**
  - **Type**
  - **Action**

A *multiplicity* of probable system operational capabilities

- Active: Alternate system components can accomplish the same thing
- Passive: A non-operational "back-up" component is available

Domain Review of Resilience

Degree of Complexity

	Materials Engineering	Systems Engineering	Social-ecological System Mgt	Critical Infrastructure Mgt
Focus	**Discrete part of the system**	**Groups of interacting parts**	**Adaptive Capacity**	**System Protection**
Purpose	**Design the system part to endure stress/minimize change**		**Design the system as a whole to tolerate stress and adapt**	**Design the system to withstand both unintentional and intentional damage**
Insights	**Assumes there is one “normal” state to which a system returns after a disturbance**		• **The “parts” of these systems are inherently adaptable** • **Explicitly recognizes humans as part of the system**	**Tightly-coupled systems with circular, reciprocal dependencies can lead to cascading or escalating failures in other systems**

Six Case Studies on Graceful Degradation

- **Hardware**
  - **Successful: USS San Francisco, Guadalcanal – 1942**
  - **Unsuccessful: Hurricane Katrina – 2005**
- **Software**
  - **Successful: Battle of Wanat – 2008**
  - **Unsuccessful: Operation *Fall Gelb* – 1940**
- **Human Interface**
  - **Successful: Task Group 77.3, Battle off Samar – 1944**
  - **Unsuccessful: 1st Army, Huertgen Forest Campaign – 1944**

Observations and Recommendations

- **Resilience requires trade-offs**
- **Resilience requires disturbances**
- **Resilience requires an acceptance of unpredictability**
- **Increasing resilience is dependent upon selecting actions that are informed by the existing system state**
- **Resilience requires a culture that:**
  - **Allows a variety of leadership styles**
  - **Fosters a high degree of trust**
  - **Uses decisions that retain all options open**
  - **Provides the capacity and capability to self-organize & reorganize**

CCJO and Graceful Degradation

- **Educate commanders and staffs to match their command philosophy to the particular requirements of each mission**
- **Regularly train the force to operate in "worst case" degraded environments**
- **Make a common set of C2 applications available as cloud services**
- **Build greater resilience into technical architectures**
- **Develop capabilities and tradecraft that provide broader intelligence to decision makers**
- **Improve the capabilities that fuse, analyze, & exploit large data sets**